ADVANCED REACTOR SAFEGUARDS

MC&A Recommendations for Liquid-Fueled MSRs

PRESENTED BY Karen Hogue, ORNL
Team: Matthew Krupcale, Logan Scott, Rabab Elzohery

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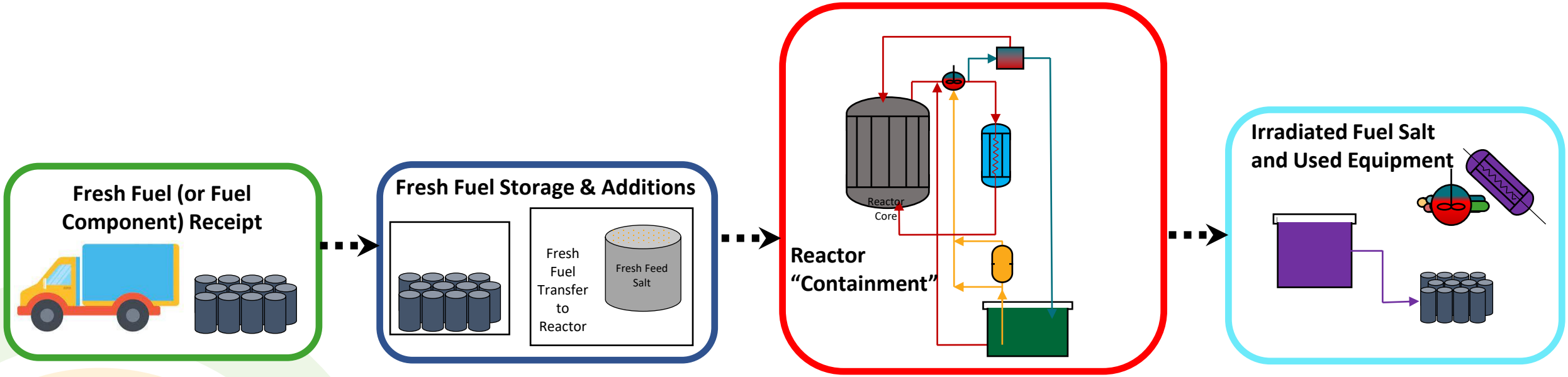
Project Motivation

- Provide recommendations to support U.S. liquid-fueled MSR vendors in developing MC&A plans
- Engage with NRC MC&A group to provide technical support and understand their expectations
- Perform technical assessments of different design variants to tailor MC&A recommendations

NRC Licensing Context

- License applicants for LWRs do not have to submit an MC&A plan
  - Fundamental Nuclear Material Control (FNMC) plan
- Fuel fabrication facilities and enrichment plants do submit FNMC plans
  - However, there is no transmutation, depletion, and only limited loss due to spontaneous decay in existing facilities
- No current NRC plans to develop a modified or MSR-specific approach for MC&A plans
  - Liquid-fueled MSRs are bulk facilities and should develop and implement MC&A plans

SNM Flow in a Liquid-Fueled MSR



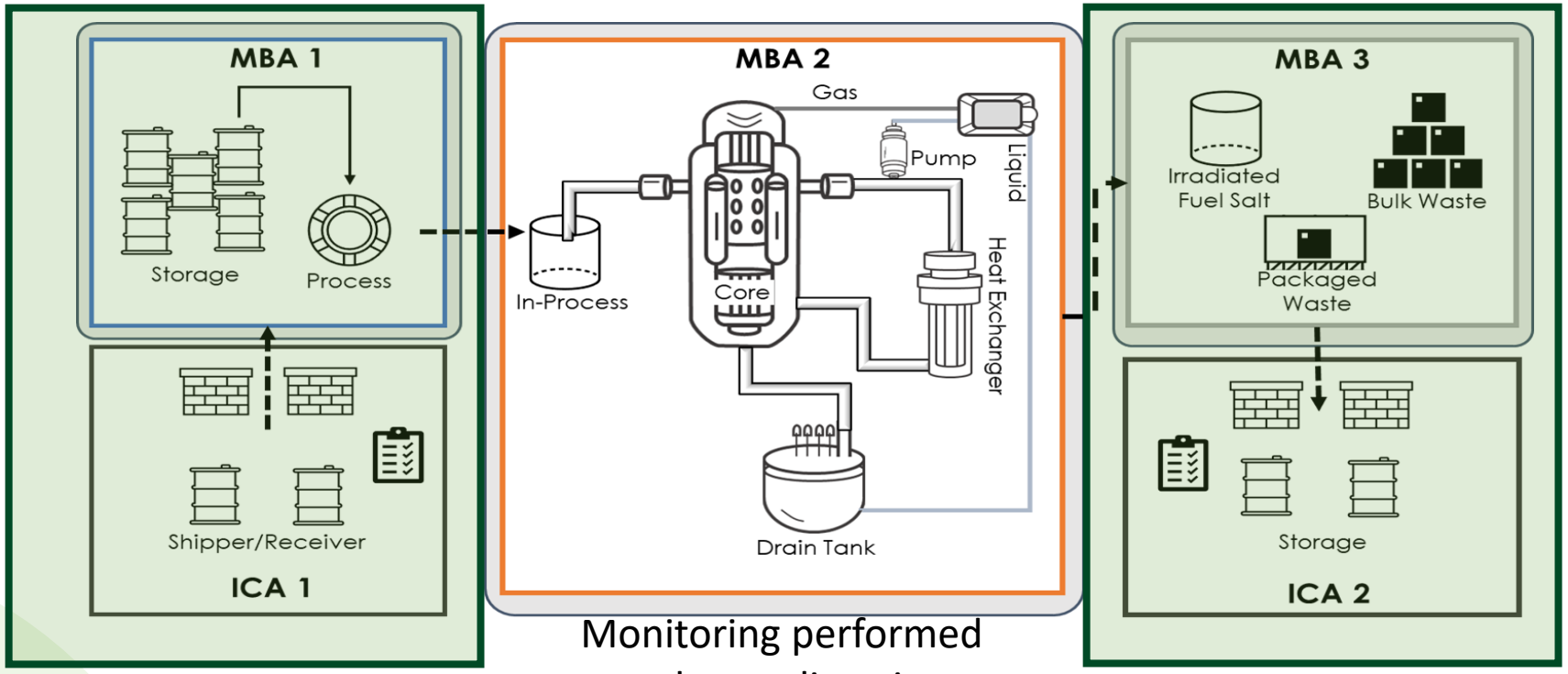
Potential Liquid-fueled MSR Approaches

- Option 1: treat a liquid-fueled MSR like any other bulk facility and directly apply Part 74 requirements
  - MSRs aren't the same as fuel fabrication facilities; SNM is in **highly radioactive** material and not accessible
  - **Expensive** to implement
  - Likely **not attainable** with current technologies
  - **Inconsistent** with NRC's approach for other reactors
  - High level of resources devoted to MC&A is (team's opinion) **not necessary** to prevent or detect diversion

Potential Liquid-fueled MSR Approaches

- Option 2: treat a liquid-fueled MSR like an LWR and do not submit an MC&A plan in license application
  - SNM in liquid-fueled MSRs is not in large, heavy items that can be counted and for which diversion has arguably more obvious indicators from a nuclear security perspective

Option 3: Proposed MC&A Approach

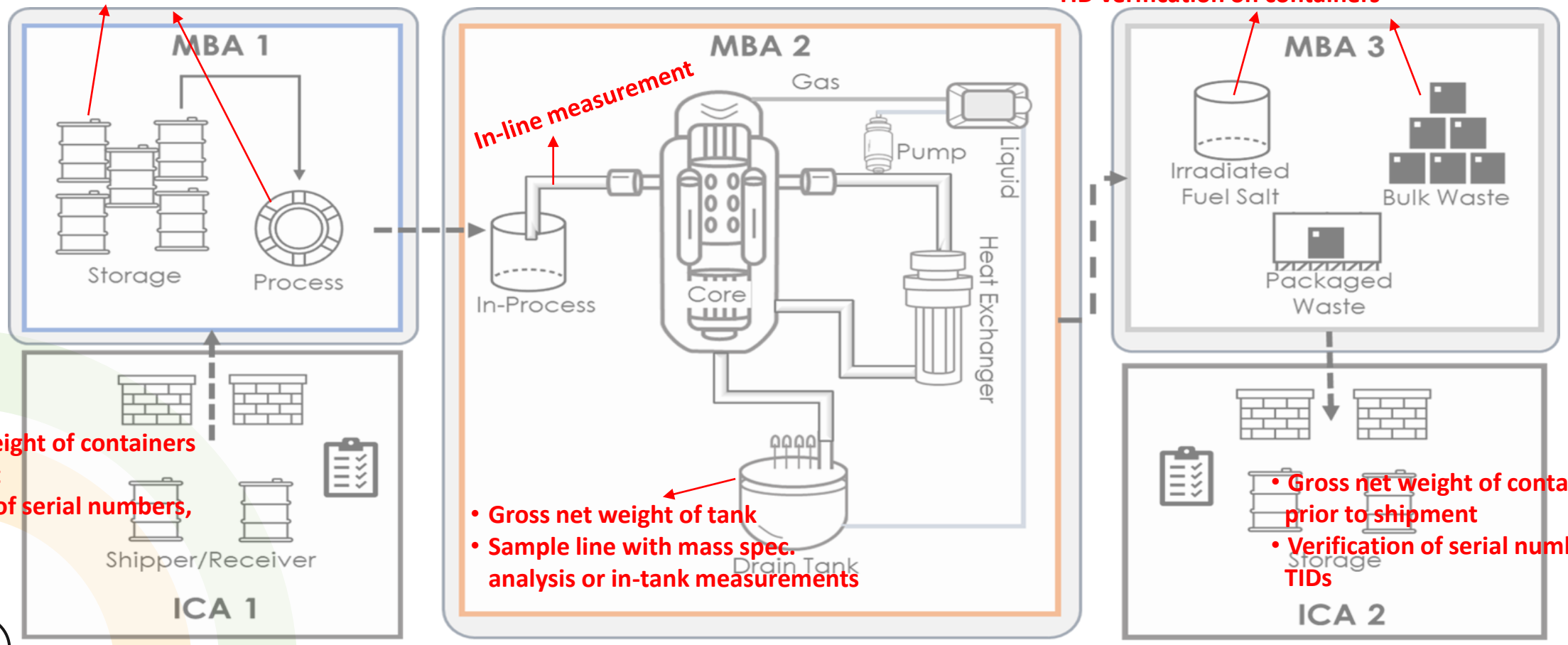


Periodic inventories performed, IDs and SEIDs calculated
(follows Part 74 requirements)

Monitoring performed to detect diversion

Periodic inventories performed, IDs and SEIDs calculated
(follows Part 74 requirements)

Conceptual draft of MC&A Elements



Note: this is an early conceptual draft of proposed MC&A elements.

MSR Variant Analysis

- Objective: Define safeguards-relevant parameters for different liquid-fueled MSR designs
- Purpose: Analyze different potential liquid-fueled MSR designs to tailor MC&A recommendations based on MSR features

MC&A-Relevant Categories of Liquid-fueled MSRs

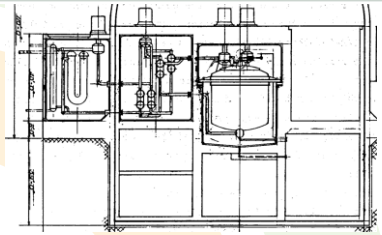
- Integral, thermal spectrum reactors
  - Essentially no processing within reactor facility
  - MC&A focuses on inputs and outputs of containment
- Thermal spectrum reactors with some processing
  - E.g., mechanical filtering of salt; filters in off-gas
  - MC&A focuses on inputs, outputs and potentially some monitoring for diversion
- Breeder designs with chemical separations
  - SNM or precursors may be separated out (e.g., co-mingled with actinides)
  - MC&A focuses on inputs, outputs, and monitoring for diversion within process streams
- Cl-fueled fast reactors with some processing
  - E.g., mechanical filtering of salt; filters on off-gas
  - MC&A focuses on inputs, outputs, and monitoring for diversion within process streams

MC&A-Relevant Design Features

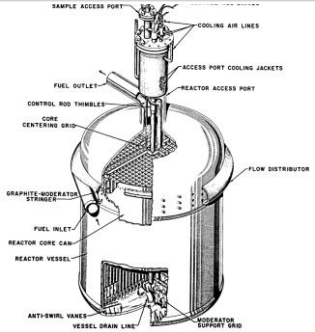
- Type of SNM
- Physical and chemical form of SNM
- Quantities of SNM
- Accessibility of SNM
  - Radioactivity of material in which the SNM is located
  - Concentration of SNM

Key Design Parameters of Example MSR Variants

Parameter		MSDR	MSRE	REBUS-3700	MOSART
Thermal power (MW)		750	8	3700	2400
Specific power (MW/MTHM$_i$)		16.4	36.7	32.2	140.0
Neutron spectrum		Thermal	Thermal	Fast	Fast
Fuel Cycle		^{232}Th+^{235}U/^{233}U+Pu	U/Pu	U+TRU/Pu	^{232}Th+TRU/^{233}U+Pu
Fresh Fuel	Chemical form	ThF_4, UF_4	UF_4	UCl_3, $TRUCl_3$	ThF_4, $TRUF_3$
	Molten salt (mol %)	LiF-BeF_2-ThF_4-UF_4 (71.5-16-12-0.5)	LiF-BeF_2-ZrF_4-UF_4 (65-29.1-5-0.9)	NaCl+(U+16.7 at% TRU)Cl_3 (55-45)	LiF-BeF_2-ThF_4-$TRUF_3$ (69.75-27.0-2.0-1.25)
	^{235}U (wt% enrichment)	93.0 (5.0 in modified design)	31.6	0.642	9.94



Ref: [1]



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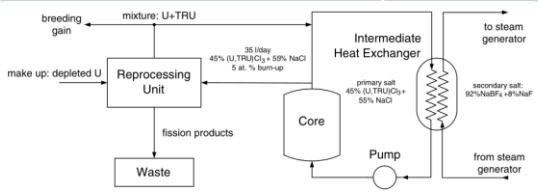

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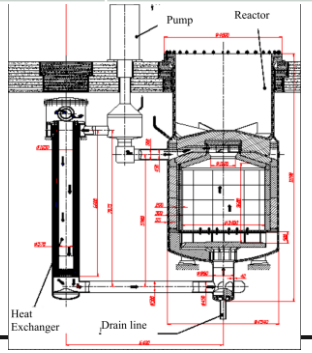

Ref: [4]

Ref: [1] – [8]

Safeguards-relevant design parameters: Initial Inventory in Fresh Fuel Salt

Initial inventory mass / concentration [kg] / [kg/L]	MSDR	MSRE	REBUS-3700	MOSART
^{232}Th	4.40e4 / 1.44e0	0 / 0	0 / 0	1.75e4 / 3.04e-1
^{233}U	0 / 0	0 / 0	0 / 0	0 / 0
^{235}U	1.73e3 / 5.65e-2	6.84e1 / 3.28e-2	6.88e2 / 1.24e-2	0 / 0
U	1.86e3 / 6.07e-2	2.18e2 / 1.05e-1	9.55e4 / 1.72e0	0 / 0
^{239}Pu	0 / 0	0 / 0	9.25e3 / 1.66e-1	5.06e3 / 8.79e-2
Pu	0 / 0	0 / 0	1.69e4 / 3.03e-1	1.03e4 / 1.78e-1
Actinides	4.58e4 / 1.50e0	2.18e2 / 1.05e-1	1.15e5 / 2.06e0	2.88e4 / 5.01e-1

Ref: [1] – [2] , [5] - [6]

Safeguards-relevant design parameters: Quantities and concentrations of SNM

Early in Life – Late in Life* mass / concentration [kg / MW] / [kg/L MW]	MSRE	REBUS-3700	Generic Cl fast reactor	MOSART
^{232}Th	9.9e-10 – 3.6e-7 / 1.0e-13 – 3.8e-11	1.8e-10 – 4.6e-9 / 2.7e-13 – 7.1e-12	1.8e-8 – 1.2e-7 / 3.1e-11 – 1.9e-10	4.3e0 - 4.1e0 / 1.9e-3 - 1.8e-3
^{233}U	7.3e-11 – 2.6e-8 / 7.6e-15 – 2.8e-12	9.1e-9 3.6e-7 / 1.4e-11 - 5.5e-10	4.6e-9 – 3.1e-8 / 7.6e-12 – 5.1e-11	2.3e-2 – 5.1e-1 / 9.9e-6 – 2.2e-4
^{235}U	8.5e0 - 6.2e0 / 8.9e-4 – 6.5e-4	1.8e-1 – 1.0e-1 / 2.8e-4 – 1.6e-4	2.8e1 - 2.7e1 / 4.6e-2 – 4.5e-2	1.9e-5 – 1.9e-2 / 8.2e-9 – 7.9e-6
U	2.7e1 - 2.5e1 / 2.8e-3 - 2.6e-3	2.6e1 - 2.6e1 / 4.0e-2 - 4.0e-2	1.4e2 - 1.4e2 / 2.4e-1 – 2.3e-1	2.4e-2 – 6.0e-1 / 1.0e-5 – 2.6e-4
^{239}Pu	5.3e-4 – 3.6e-1 / 5.5e-8 – 3.8e-5	2.5e0 - 2.7e0 / 3.9e-3 / 4.1e-3	1.8e-1 – 8.9e-1 / 3.0e-4 – 1.5e-3	1.2e0 - 6.5e-1 / 5.2e-4 – 2.8e-4
Pu	5.3e-4 – 3.8e-1 / 5.5e-8 – 4.0e-5	4.6e0 - 4.7e0 / 7.0e-3 - 7.2e-3	1.8e-1 – 9.0e-1 / 3.0e-4 – 1.5e-3	2.5e0 - 2.4e0 / 1.1e-3 - 1.0e-3
SNM	8.5e0 - 6.7e0 / 8.9e-4 - 6.9e-4	4.8e0 - 4.8e0 / 7.3e-3 - 7.3e-3	2.8e1 - 2.8e1 / 4.7e-2 – 4.6e-2	2.6e0 - 3.0e0 / 1.1e-3 – 1.3e-3
Radioactivity concentration [Ci/L MW]	2.3e3 - 2.7e3	1.1e2 - 1.1e2		9.7e1 - 1.0e2

Ref: [5] - [6], [9]

*REBUS, MOSART: Early in life = 0.2 years, Late in life = 5 years; Generic Cl: Early in life = 1 year, Late in life = 5 years; MSRE: Early in life = 5 days; Late in life = 5 years

Conclusions

- Modeling and simulation are being leveraged to estimate safeguards-relevant parameters for different types of liquid-fueled MSR designs and tailor MC&A recommendations
- The team recommends a novel MC&A approach strategy in license-applications to the NRC and is discussing this with the NRC MC&A group
  - Periodic inventories will be conducted on MBAs outside of reactor containment boundaries
  - Containment and surveillance (i.e., TIDs, cameras, etc.) will supplement material accountancy
  - In some (most) liquid-fueled MSRs, monitoring for diversion should be performed within containment at points identified through a diversion analysis

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[3] Mourogov, A. and P. M. Bokov. 2006. "Potentialities of the fast spectrum molten salt reactor concept: REBUS-3700." *Energy Conversion and Management* 47(17): 2761-2771.

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[5] Lo, A., F. Bostelmann, D. Hartanto, B. Betzler, and W. A. Wieselquist. 2022. *Application of SCALE to Molten Salt Fueled Reactor Physics in Support of Severe Accident Analyses*. Tech. Rep. ORNL/TM-2022/1844, Oak Ridge National Laboratory.

[6] Shoman, N. and M. Higgins. 2022. *FY22 Final Report on Molten Salt Reactor Safeguards Modeling*. Tech. Rep. SAND2022-11048 O, Sandia National Laboratories.

[7] Rykhlevskii, A., B. R. Betzler, A. Worrall, and K. D. Huff. 2019. "Fuel Cycle Performance of Fast Spectrum Molten Salt Reactor Designs." International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2019): 342-353.

[8] Betzler, B. R., A. Rykhlevskii, A. Worrall, and K. D. Huff. 2019. "Impacts of Fast-Spectrum Molten Salt Reactor Characteristics on Fuel Cycle Performance." Global 2019 International Fuel Cycle Conference: 514-521.

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